# REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-98-
0706



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|---|---|---|
| 1. AGENCY USE ONLY *(Leave blank)* | 2. REPORT DATE<br>6 October 1998 | 3. REPORT TYPE AND DATES COVERED<br>Final Technical Report 15 Mar 97 to 14 Sep 98 |

**4. TITLE AND SUBTITLE**
Vacuum Diagnostics Facility for Electric Propulsion Studies

**5. FUNDING NUMBERS**
F49620-97-1-0195

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**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
AFOSR/NA
801 N Randolph St Rm 732
Arlington VA 22203-1977

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
F49620-97-1-0195

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION AVAILABILITY STATEMENT**
Approved for public release; distribution unlimited.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*

We have completed the design and installation of a facility at Stanford University for the studies of plume and discharge plasma structure of xenon-ion thrusters used in space electric propulsion. The low pressures provided by the facility during thruster testing provides an improved environment for evaluating thruster performance, including near-field and far-field plume properties (e.g., particle velocities, densities, temperatures), which are needed to evaluate the spacecraft compatibility of these advanced thrusters. The facility as designed and installed includes a stainless steel vacuum chamber that is cryogenically-pumped, and instrumented with electrical and optical ports for plasma and laser diagnostics. The facility will permit a tank pressure of less than 5 x 10 Torr while flowing 2.7 mg/sec of xenon propellant.

**14. SUBJECT TERMS**

**15. NUMBER OF PAGES**
14

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | UL |

# FINAL REPORT: FY 97 DURIP

(From 3 March 1997 to 14 September 1998)

## Vacuum Diagnostics Facility for Electric Propulsion Studies

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GRANT NUMBER: F49620-97-1-0195
START DATE OF CONTRACT: 15 March 1997
END DATE OF CONTRACT: 14 September 1998

Executive Summary

We have completed the design and installation of a facility at Stanford University for the studies of plume and discharge plasma structure of xenon-ion thrusters used in space electric propulsion. The low pressures provided by the facility during thruster testing provides an improved environment for evaluating thruster performance, including near-field and far-field plume properties (e.g., particle velocities, densities, temperatures), which are needed to evaluate the spacecraft compatibility of these advanced thrusters. The facility as designed and installed includes a stainless steel vacuum chamber that is cryogenically-pumped, and instrumented with electrical and optical ports for plasma and laser diagnostics. The facility will permit a tank pressure of less than 5 x $10^{-6}$ Torr while flowing 2.7 mg/sec of xenon propellant. The project also included the procurement, installation, and testing of a Nd:$YVO_4$ laser-pumped Ti:Sapphire laser for use as a laser-fluorescence diagnostic probe. In addition, the project provided the funds to procure a four-axis translation stage to support and move the thruster, as well as the mechanical components needed to assemble an inverted-pendulum thrust stand.

## SUMMARY AND BACKGROUND

The Mechanical Engineering Department at Stanford University has been conducting research on electric propulsion for several years. Over the last three years, the focus of the program has shifted to studying Hall-type ion thrusters. Providing a suitable high vacuum, space-like environment for Hall thruster experiments has led to many problems related to misinterpretation of measured performance and plasma properties owing to ground-base tank limitations. A clean, high-pumping speed cryogenic-driven vacuum chamber will solve many of these problems. The selection of the pumping mechanism was motivated by the fact that we have found contamination in the form of the deposition of oil on the chamber walls and on the thruster itself in our existing oil diffusion pumped facility due. The new facility was also motivated by the need to move towards a much lower experimental background pressure, to lessen the effects of having walls very near the thruster, and also to increase optical access to the thruster. Our current chamber can provide a background pressure of about $1 \times 10^{-4}$ Torr at 2.7 mg/s of xenon. The new vacuum facility will be capable of maintaining $5 \times 10^{-6}$ Torr at this flow rate. All of these concerns led to the choice of a large, cryopumped facility. The facility is also instrumented with a translation stage for in-vacuum thruster motion control, and an inverted-pendulum thrust stand for direct thrust measurements.

In addition to the selection and installation of a new vacuum facility, the DURIP award provided for the installation of an advanced flow diagnostic capability. The proposal detailed the benefits of implementing continuous-wave laser induced fluorescence for advanced flowfield characterization of ion thrusters. In particular, the proposal argued in favor of purchasing an all-solid-state laser technology that provides tunability over a broad wavelength range (690 - 970 nm). This is achieved with modern-day solid state pumped ring lasers. We have purchased a Nd:$YVO_4$ pumped Ti:Sapphire laser for this purpose, and have installed, and tested this laser for use as a diagnostic on Hall thrusters in our existing vacuum chamber.

The following paragraphs summarize our progress in the procurement, installation, and testing of the complete facility, including the advanced laser diagnostics system.

(i) Installation of Cryogenically-Pumped High-Vacuum Chamber and Accessories

**CONSTRUCTION**: The new high vacuum facility was designed by senior graduate student William Hargus and constructed by Dynavac Corporation. The facility consists of two large chambers connected by flanges [see schematic illustration in Figure 1]. A photograph of the vacuum chamber installed in the laboratory is shown in Fig. 2. A complete set of engineering drwings, provided by Dynavac to our specification, is included in the Appendix. The test section is a straight tube in which experiments will be performed. This section is connected to a large, "T-shaped" pumping section with a CVI Torrmaster 1200 cryopump mounted on each end of the "T". This shape was chosen by William Hargus and endorsed by Dynavac because it provides both a high conductance and a low heat-load on the cryopumps.

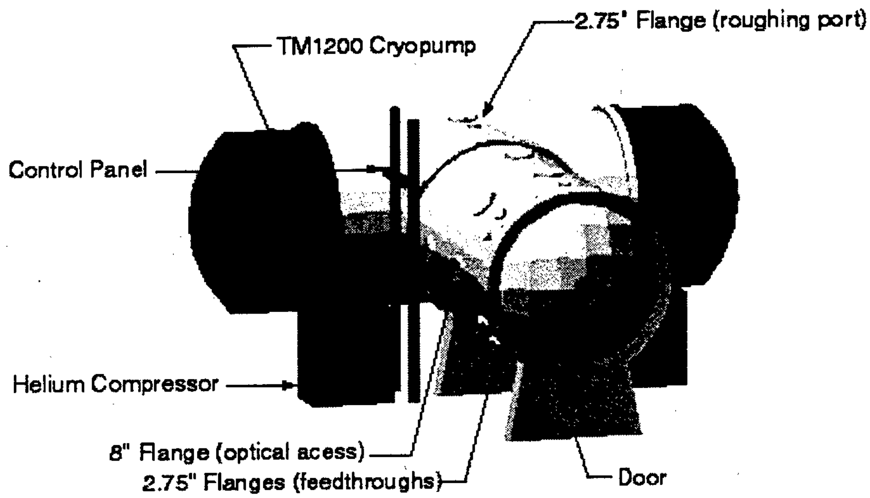



Figure 1. Schematic illustration of the cryogenically-pumped vacuum facility of electric propulsion studies.

The two sections were rolled out of stainless steel. Both sections have an outer diameter of 53 inches (4' 5") and a wall thickness of 3/8 of an inch. The test section is 7 feet long. The pumping section is 7 feet, 6 inches long. The distance from the end of the test section to the centerline of the pumping section is approximately 3 feet. Thus, gas molecules ejected from a Hall thruster in the chamber will travel over 8 feet before their first collision with a wall. Four stainless-steel Unistrut pieces are welded inside the test section 4.5" above the chamber bottom to provide a mounting surface for experiments.

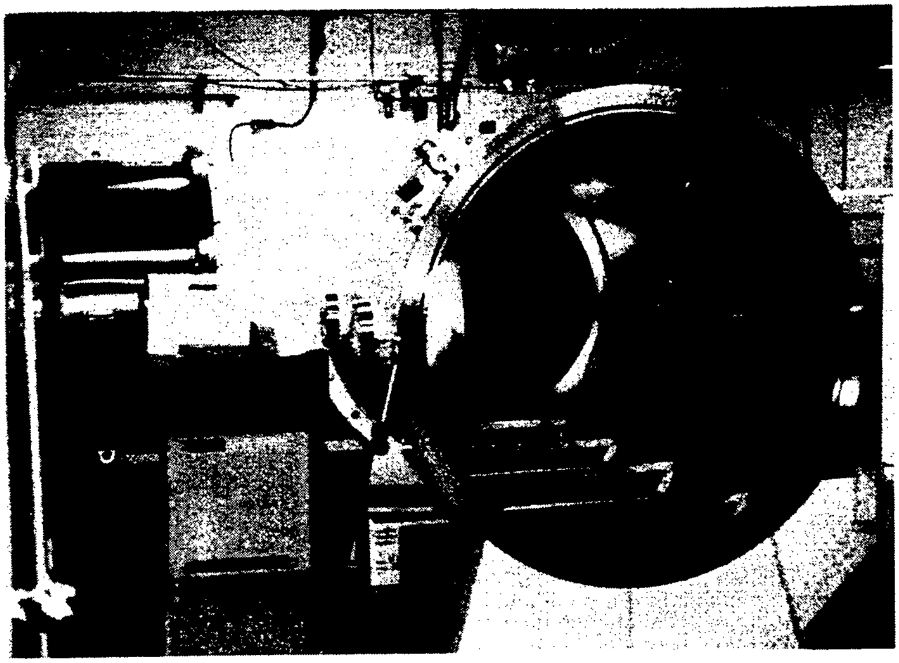


Figure 2. Photograph of the cryogenically-pumped vacuum facility of electric propulsion studies.

**PUMPS:** The pumping section ("T section") of the chamber is attached to two Torrmaster 1200 cryopumps, provided by Consolidated Vacuum Incorporated (CVI). Each pump is capable of pumping 57,000 Liters per second of nitrogen, or about 25,000 Liters per second of xenon. The pumps utilize a multi-stage helium refrigerator to cool an array of panels to about 15K. CVI provided two helium closed-circuit scroll compressors to drive the refrigerator units on the cryopumps. The pumps are turned on after a rough vacuum has been obtained with the lab's existing roughing facility, and gas molecules inside the chamber are near the free-molecule limit. When a gas molecule strikes one of the cryopanels in the cryopump, it freezes and sticks. As these molecules are removed from the chamber, a high vacuum is attained.

Liquid nitrogen is supplied to a baffle separating the cryopanels from the outside of the chamber. This gives the cryopanels a low heat load, which allows them to operate more efficiently. Each cryopump is fitted with temperature sensors. These consist of two Lakeshore Cryotronics model DT470 silicon diode temperature sensors mounted on each cryopanel and one type-T (copper-constantan) thermocouple attached to each liquid nitrogen baffle. The silicon-diode sensor is capable of measuring temperatures down to 1.4 K. The type-T thermocouple is capable of

measuring temperatures lower than 65 K. The electronic monitors for these sensors are described below.

**ACCESS:** The test section is fitted with eight 8" Conflat-style flanges and thirteen 2.75" Conflat-style flanges. The test section is fitted with two 8" flanges and one 2.75" flange. The chamber is held 20 inches above floor level by four support cradles. This puts the horizontal flanges about 4 feet above the floor level, an excellent level for optical access. The large number of flanges will also allow many instrumentation and power feedthroughs, allowing many experiments to be run simultaneously or in succession without bringing the chamber back to atmosphere.

Several attachments and feedthroughs were purchased with the chamber from various suppliers. These include: (a) one quartz view port on 2.75" Conflat flanges for light collection and laser-beam access along the thrust axis; (b) two glass view ports for the 8" Conflat flanges for observation of the thruster and light collection at 90°angles to the thrust axis; (c) one 2-port fluid feedthrough on a 2.75" Conflat flange for Xe gas input to the thruster and the cathode; (d) one 4-conductor single-ended BNC feedthrough on a 2.75" Conflat flange to connect to electrostatic probe experiment and diagnostics; (e) two 20-wire instrumentation feedthroughs on a 2.75" Conflat flange for various electronics penetration into vacuum; (f) two 10-wire instrumentation feedthroughs on 2.75" Conflat flange of connecting to stepper motors, thrust stand components, and other electronics inside the chamber; (g) one 4-conductor medium-high current power feedthrough on 2.75" Conflat flange for power input to the thruster and cathode; (h) one ¼" VCR male-2.75" Conflat adapter that provides a vacuum connection to the thermocouple vacuum gauge; and (i) two 8" Conflat flanges to 2.75" Conflat adapter flanges which allow miscellaneous use of 2.75" feedthroughs at 8" flange locations.

**ACCESORIES:** Operating a large vacuum facility is extremely complicated. A large number of accessories were purchased to allow one person to monitor and operate the vacuum system. Most of these accessories were purchased on the original equipment grant account.

Several accessories are necessary for obtaining a rough vacuum inside the chamber and for monitoring the pressure inside the test chamber. These include: (a) one flexible stainless steel vacuum hose to connect the chamber to the existing mechanical pump facility; (b) one solenoid vacuum valve to open/close the connection to the mechanical pump facility; (c) one molecular sieve with heater to prevent back-streaming of mechanical pump oil from contaminating the cryopanels; (d) two thermocouple (TC) vacuum gauges (one already existing) to measure pressure in the chamber test section and in the roughing line; (e) one ionization gauge on a 2.75" Conflat flange to measure the pressure in the chamber test section in medium-high vacuum; (f) one Varian senTorr BA2 vacuum gauge readout (and cables) to monitor and display readings from both TC gauges and ionization gauge, and; (g) one right-angle bellows valve on a 2.75" Conflat flange to act as a vent valve for the chamber.

The cryompumping system is both expensive and delicate. Several accessories were purchased to address the problems of operating this system. These consist of electronics to monitor the temperature of the cryopumps and cryogenic liquid-handling equipment to allow the transfer of liquid nitrogen to cool the cryopump shrouds. The following is a description of these items: (a) one Lakeshore Cryotronics model 218E temperature readout to monitor and display temperature from all four silicon diode temperature sensors; (b) one Omega model DP462-TC thermocouple readout to display temperature of both type-T thermocouple sensors; (c) two LN2/GN2 separators (provided by CVI) to allow boil-off from LN2-cooled baffles to leave the cryopump shroud; (d) two VBS vacuum-jacketed hoses for LN2 transfer to safely deliver LN2 from a dewar to a cryopump shroud, and ; (e) Two cryogenic shutoff valves for LN2 transfer to safely replace empty LN2 dewars during cryopump operation.

Some accessories that are still under assembly include:

(a) an electric propulsion thrust stand of the NASA Lewis design, now supplied by Space Age Industrial Design. A version of this thrust stand (on loan from Philips Laboratory was used by our laboratory in prior studies of Hall thruster performance characterization. The components (less electronics) have been purchased under this grant, and the thrust stand is presently being assembled.

(b) a Parker 2-axis translation table with two high-vacuum motors for 2-axis translation remotely position the thruster for optical alignment and for electrostatic probe experiments.

(ii) Procurement, Assembly, and Testing of Nd:$YVO_4$-pumped Ti:Sapphire Laser

The DURIP award provided for the purchase of an all solid-state state-of-the-art narrow linewidth ring laser for advanced diagnostics of electric rocket plumes. As stated in the original proposal, we identified the model 899-21 Ring Laser System from Coherent, Inc., as the most suitable system for our present interest in the physics of xenon plasma plumes. The Coherent model 899-21 Ring Laser System is a flexible, convertible ring laser that can be operated as a conventional dye ring laser, or as a solid state ring laser using titanium:sapphire as the gain medium. Active frequency control, achieved with an electronic servo loop and reference cavity, is capable of producing line widths as narrow as 500 kHz RMS. Single mode frequency scanning in ranges up to 30 GHz is possible by continuously varying the cavity length with a rotating galvanometer driven Brewster plate. In the titanium:sapphire configuration currently being used, it is tunable from 680 to 1025 nm with appropriate optics. The titanium:sapphire configuration is advantageous since it does not produce toxic and potentially carcinogenic waste products as do ring dye systems.

The 899-21 ring laser is pumped with a Coherant Verdi high power continuous wave solid state (Nd:$YVO_4$) pump laser. The Verdi is a single frequency diode pumped ring laser producing up to 5W at 532 nm. The efficiency of this pump laser is such that it is air cooled and requires less than 10 A at 120 VAC. Argon ion lasers previously used to provide similar output powers consume approximately 10 x the power required by the Verdi. In addition, argon ion lasers require extensive water cooling. The single frequency operation of the Verdi also is advantageous. It enhances the linewidth characteristics of the 899-21 ring laser it pumps. This differs from argon ion lasers which actually lase at a number of wavelengths.

At the writing of this report, the laser facility has been brought to fully operational status, and has already been used to collect data from our existing Hall thruster vacuum chamber (diffusion

pumped). In our Hall thruster studies, we have measured the neutral and ionic xenon species velocities using LIF excitation of the XeI 6s[3/2]$2^{o}$-6p[3/2]2 (centered at 823 nm) and the XeII 5*d*[4] 7/2 - 6*p*[3]5/2 (centered at 834.7 nm) electronic transitions respectively. These transitions are ideally suited for interrogation with the Ti:Sapphire system, as they are in the range where the laser's output is the strongest. The former transition has been studied extensively in our laboratory, and the atomic constants of the transitions are well known. This is not the case for the 834.7 nm transition, however, for LIF measurements aimed at only determining the velocity of the plasma flow, it is often convenient to probe more accessible transitions for which there may be incomplete knowledge of the isotopic and nuclear spin splitting constants. An additional convenient feature of this transition is a strong line 6*s*[2]3/2 - 6 *p*[3]5/2 transition at 541.9 nm emanating from the same upper state. This allows for improved signal to background levels as it is a nonresonant detection scheme.

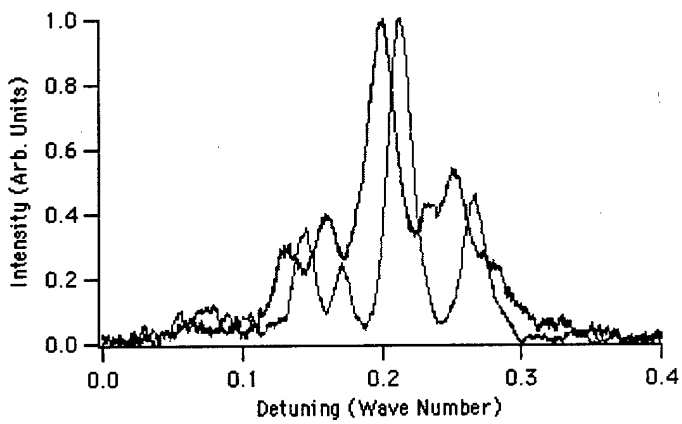



Figure 3. LIF spectra of the 823 nm neutral xenon transition measured in a stationary reference glow discharge (red) and at the exit plane of our Hall thruster (black). These data were taken with the recently acquired Ti:Sapphire ring laser system. The relative shift in the spectra corresponds to a Doppler-shift associated with a 320 m/s flow.

Figure 3 above shows typical neutral xenon 823.2 nm LIF excitation scan acquired with the laser system described above. The black trace is the laser induced fluorescence collected from the probe volume near the exit plane of a Hall thruster operating at a nominal discharge voltage of 100V. The probe volume is determined by the intersection of the probe laser beam and its image focused on an optical aperture. The red trace is a rectified absorption trace of the same transition taken with the laser passing through a xenon glow discharge lamp. It provides a stationary

reference of the probed transition. The scan is approximately 12 GHz (0.4 $cm^{-1}$) wide. The Doppler shift between the two line shapes is due to the relative velocity along the direction of propagation of the probe beam of the atoms. In this case, the Doppler shift corresponds to a velocity of approximately 320 m/s.

The Ti:Sapphire laser is thus already finding utility in our laboratory, despite the continuing assembly and testing of our cryogenically-pumped chamber. We anticipate that a fully functional chamber will be online by the end of 1998, and that we shall be able to report on LIF studies of Hall thrusters in this chamber by mid 1999.

PERSONNEL SUPPORTED ON THIS GRANT (Directly, or Partially)

The grant provided for some technical support to aid in the installation of the vacuum facility. No direct funds were provided for the P.I. or graduate students.

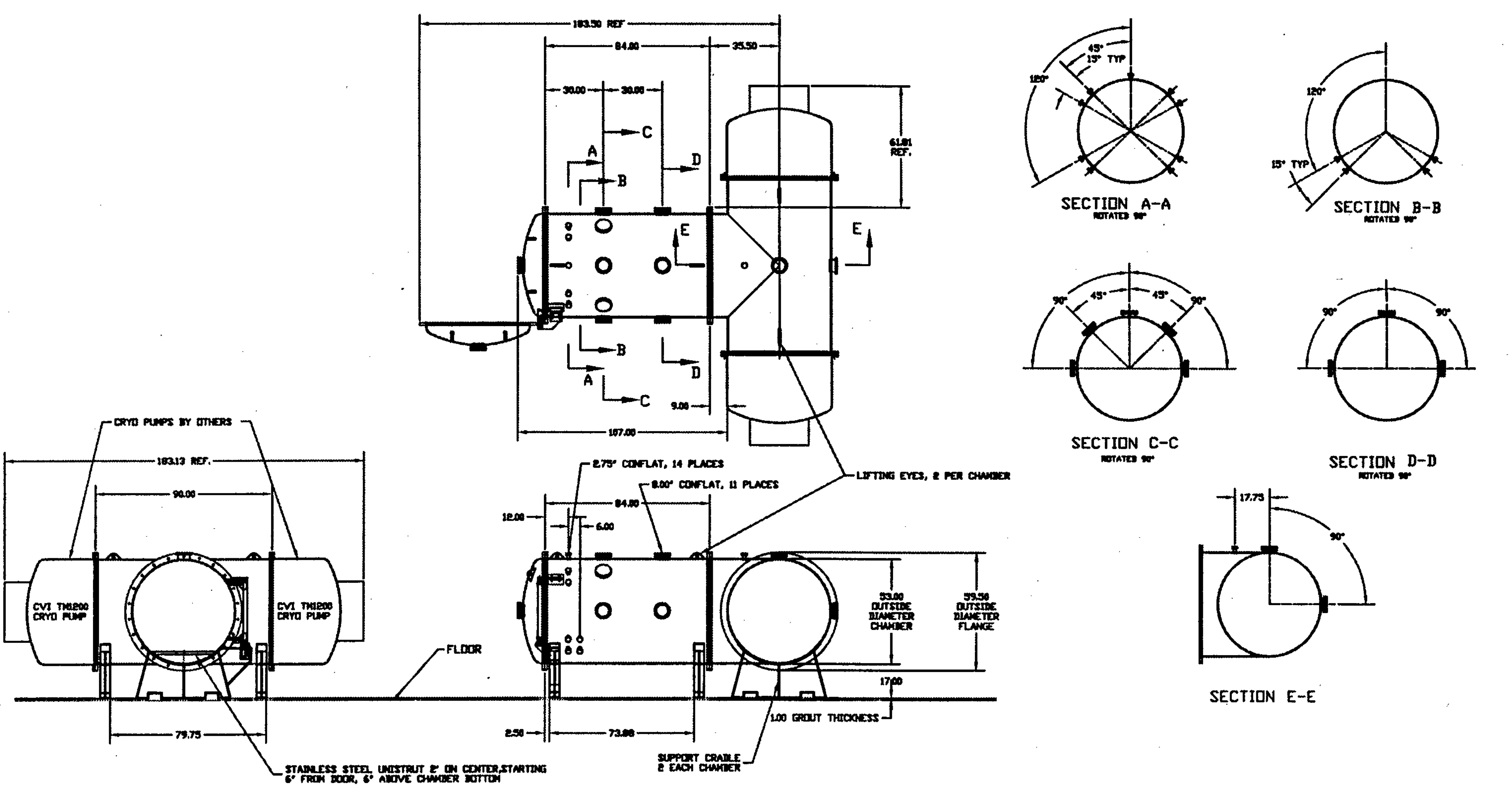
# APPENDIX

Engineering Drawings for the Vacuum Chamber

| BM #111009 | 54" STANFORD CHAMBER ASSEMBLY | REV. A |
|---|---|---|
| Dwn By: ENP | Date: 6/12/97 | App'd By: Date: |
| Next Assy: 511009 | | Used On: 8744 |

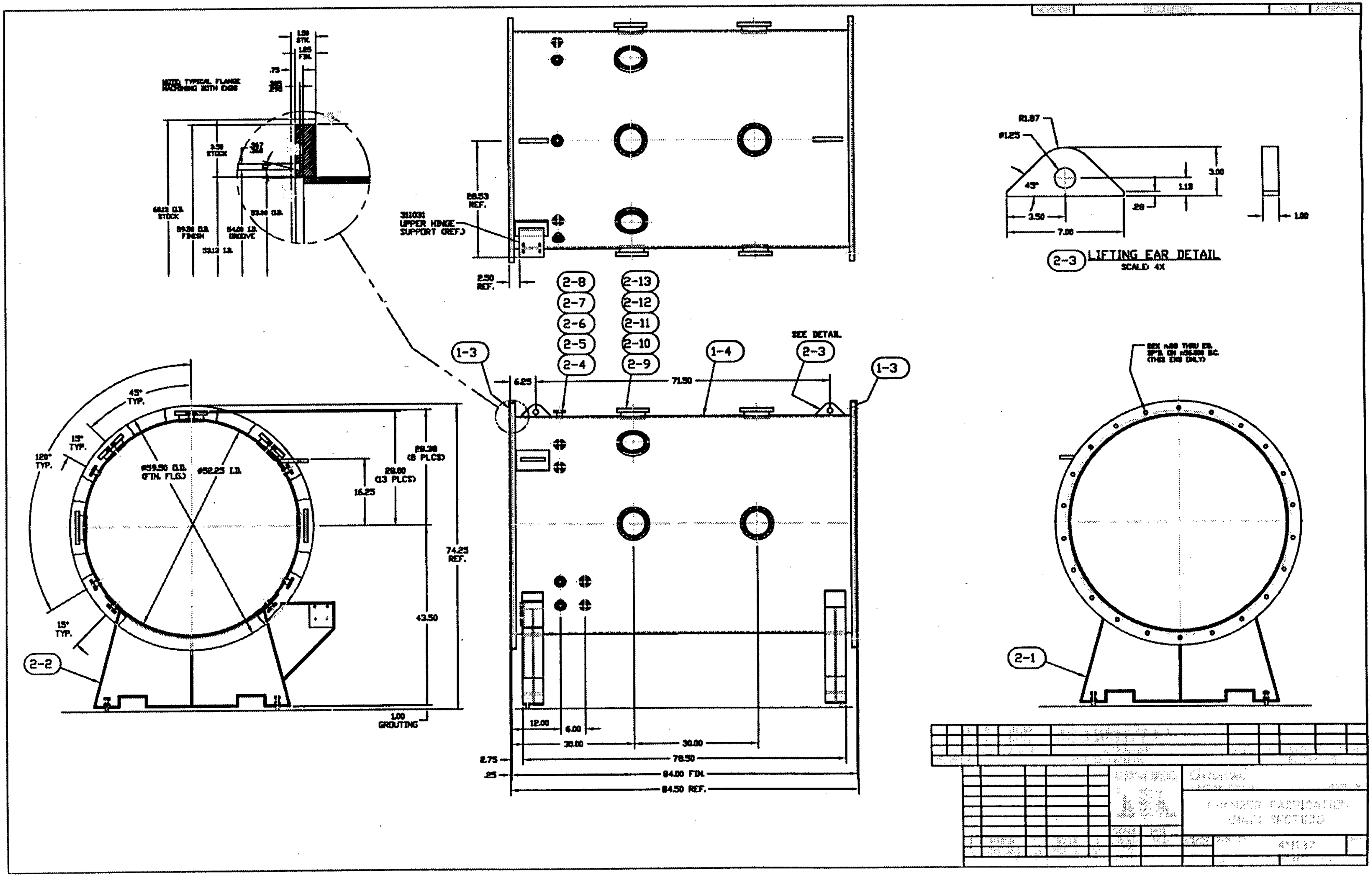
| IT. | G3 | G2 | G1 | DWG. No. | DESCRIPTION | MAT'L. | QTY. | DELIV. | P.O.# | CODE |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | 1 | CHM#1 BDY | .38 THK PLATE 89.00 WIDE X 165.38 LONG, ROLLED TO 53" O. D., #4 POLISH INSIDE | 304 SS | | | | |
| 2 | | | 1 | CHM#1 TEE | .38 THK PLATE X 35.00 WIDE X 165.38 LONG ROLLED TO 53" O. D., #4 POLISH INSIDE | 304 SS | | | | |
| 3 | | | 6 | FLANGES | 1.50 THK X 3.50 WIDE X 177.88 LONG ROLLED HARDWAY TO 53.12 I. D. | 304 SS | | | | |
| 4 | | | 1 | CHM#2 BDY | .38 THK PLATE X 83.00 WIDE X 165.38 LONG ROLLED TO 53" O. D., #4 POLISH INSIDE | 304 SS | | | | |
| 5 | | | 1 | DOOR | ASME F & D HEAD, .25" THK X 53" O. D. X 1.50 S.F., #4 POLISH INSIDE, SQUARE EDGE | 304 SS | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |

| REV. | DESCRIPTION | DATE | APPD. |
|---|---|---|---|
| | | | |
| A | ITEM #1 WAS 168.50 LONG & 54" OD; ITEM #2 WAS 168.50 LONG & 54" OD; ITEM #3 WAS 3.00 WIDE & 178.50 LONG; ITEM #4 WAS 168.50 LONG & 54" OD; ITEM #5 WAS 54" OD | 6/19/97 | |
| | | | |
| | | | |




1. FINISH EPOXY PAINT, "DYNAVAC WHITE"

NOTES:



MOD. TYPICAL FLANGE MACHINING BOTH ENDS
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1.05 FIN.
.75
3.50 STOCK
66.13 O.D. STOCK
59.50 O.D. FINISH
54.00 I.D. GROOVE
53.12 I.D.
311031 UPPER HINGE SUPPORT (REF.)
28.53 REF.
2.50 REF.
2-3
LIFTING EAR DETAIL
SCALE 4X
R1.87
ø1.25
45°
3.50
7.00
3.00
1.13
.28
1.00
2-4
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2-6
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2-8
2-9
2-10
2-11
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2-13
1-3
1-4
SEE DETAIL
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71.50
12.00
6.00
30.00
78.50
84.00 FIN.
84.50 REF.
2.75
.25
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15° TYP.
120° TYP.
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ø52.25 I.D.
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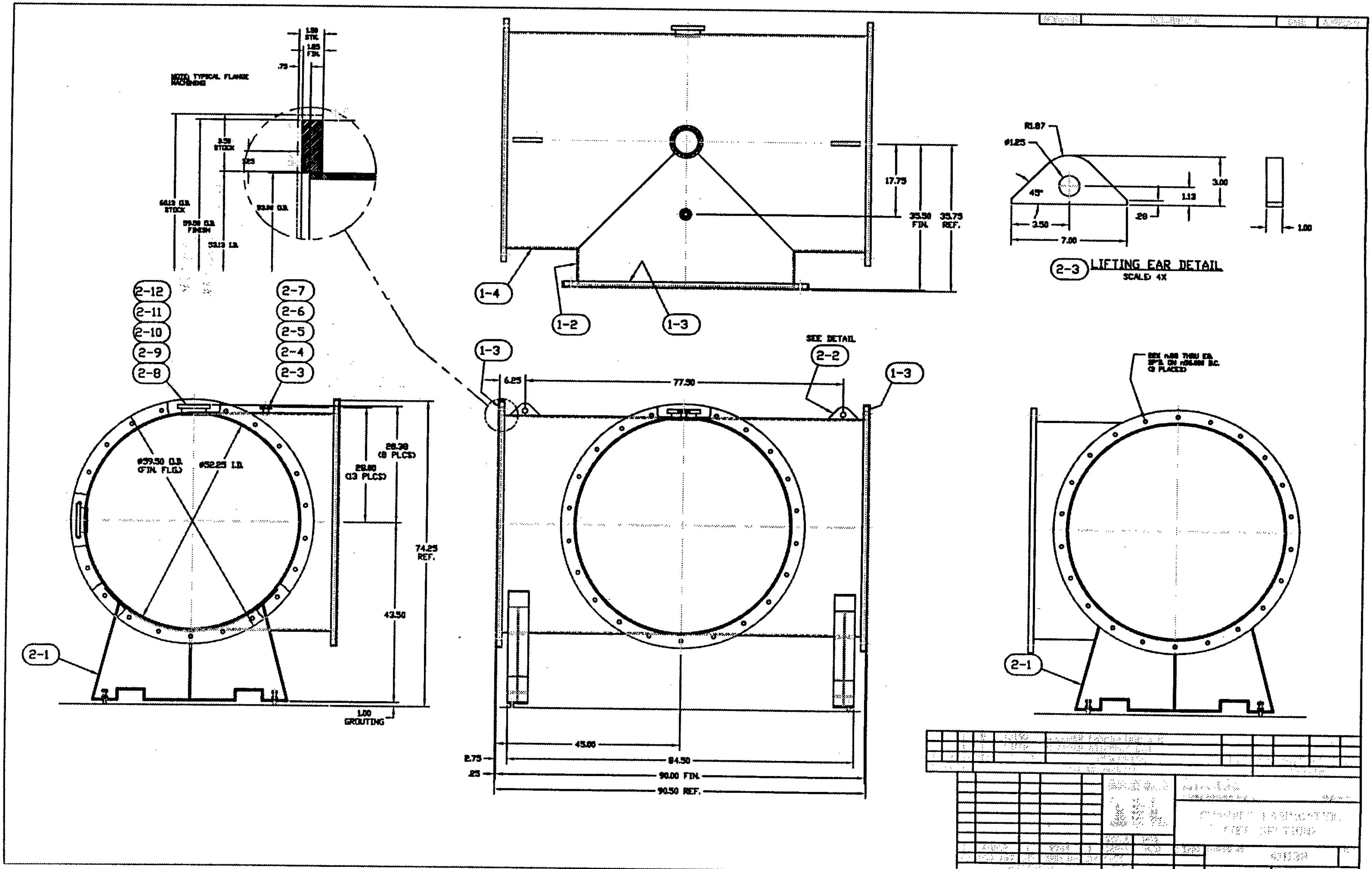
28.00 (13 PLCS)
16.25
74.25 REF.
43.50
1.00 GROUTING
2-2
2-1



NOTE: TYPICAL FLANGE MACHINING
1.50 STK.
1.25 FIN.
.75
3.50 STOCK
.25
64.13 O.D. STOCK
59.50 O.D. FINISH
53.13 I.D.
53.00 O.D.
2-12
2-11
2-10
2-9
2-8
2-7
2-6
2-5
2-4
2-3
ø59.50 O.D. (FIN. FLG.)
ø52.25 I.D.
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28.80 (13 PLCS)
74.25 REF.
43.50
1.00 GROUTING
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1-4
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SEE DETAIL
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77.50
45.00
84.50
90.00 FIN.
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.25
R1.87
ø1.25
45°
3.00
1.13
.28
3.50
7.00
1.00
2-3 LIFTING EAR DETAIL
SCALE: 4X